PPFX for DUNE

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INTRODUCTION

- Goals:
  - Obtain first Estimate of DUNE's hadron flux uncertainties
  - Obtain an over all interaction map of all particles and sort out the interactions covered and not covered by current Thin Target Experiment
  - Improve the DUNE flux prediction using the external hadron production data

INTRODUCTION: METHOD

- Use PPFX, a package developed by Leo Aliaga for MINERvA with successful results.

OVERVIEW OF PPFX

- Uses dk2nu neutrino ntuples made by g4lbnf for each neutrino events as inputs
- Identifies events covered by current thin target experiments
- Extend the data coverage of thin target experiments wherever possible

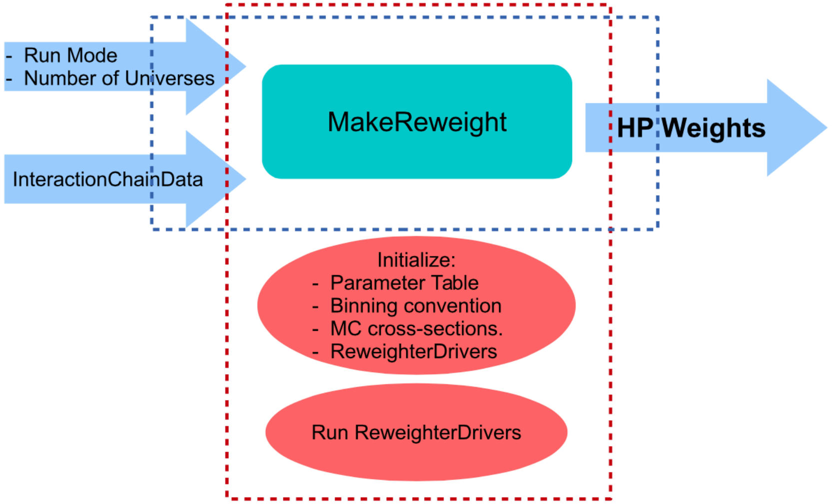


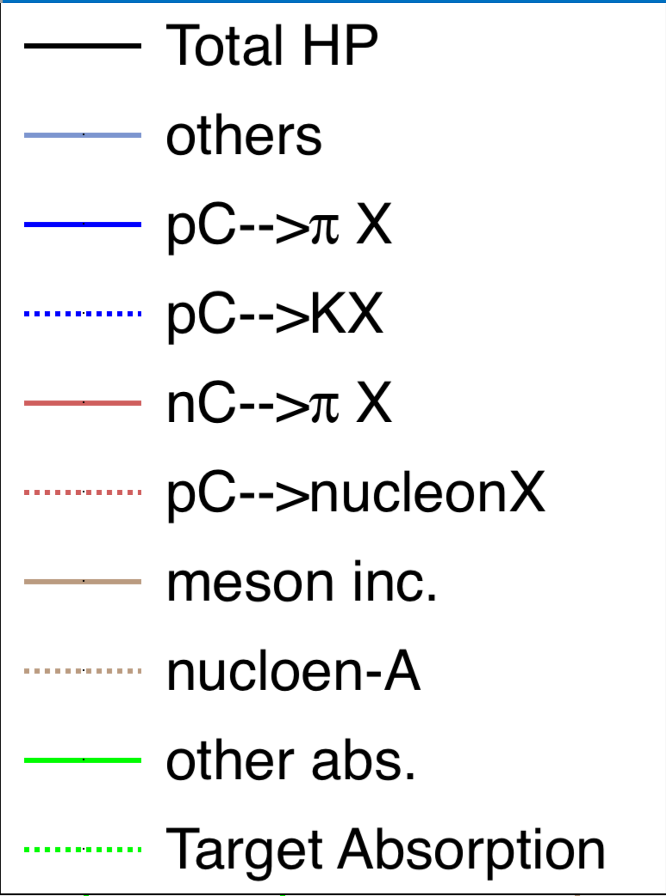
FIG. 4.46: PPFX flowchart.

PPFX VALIDATION

PPFX Validation

- PPFX before and after modification gives same result.
- G4lbnf before and after modification gives same result.

How Uncertainties are Categorized

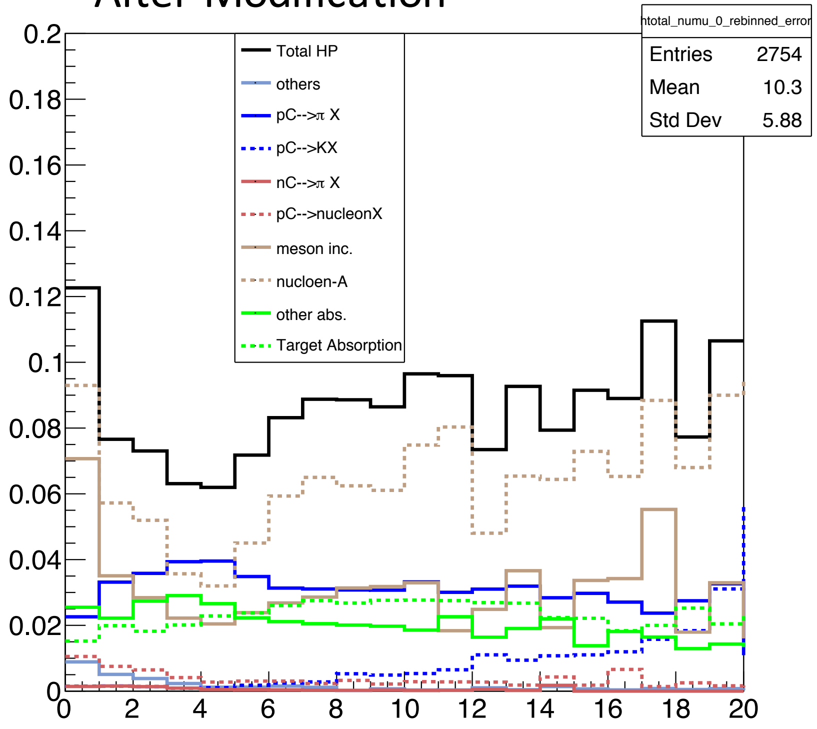


1. Total Hadron Production Interactions
2. Interactions (excluding 8. interactions) not covered by any of the below categories.
3. Pion production in proton Carbon Interaction
4. Kaon production in proton Carbon Interaction
5. Pion production in neutron Carbon Interaction
6. Nucleon production in proton Carbon Interaction
7. Meson incident Interactions
8. Nucleon Incident interactions not covered by any data
9. Absorption outside the target
10. Absorption inside the target

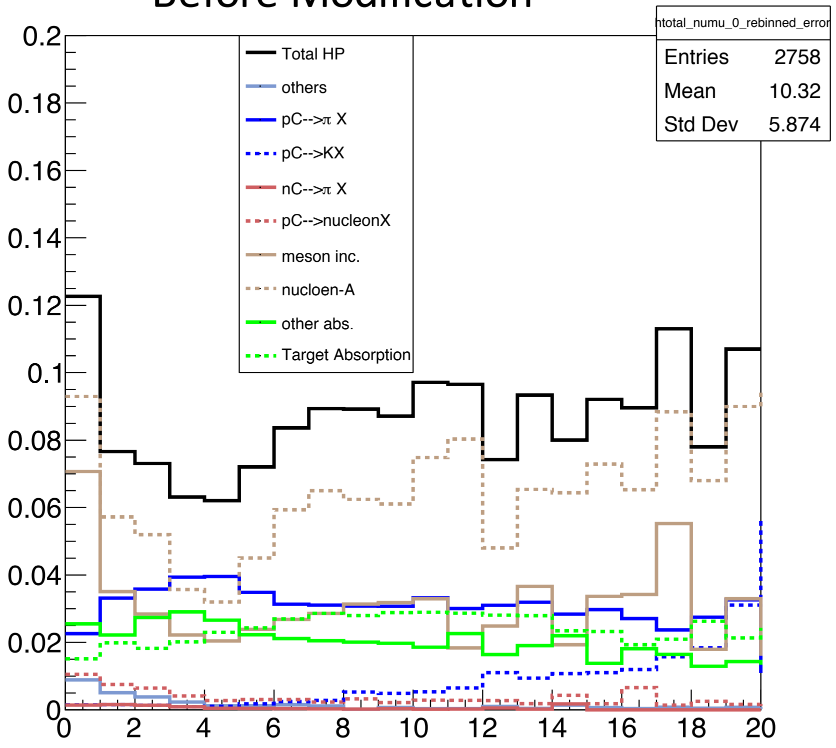
2 contains the interactions 3,4,5,6,7,9 and 10 category interactions that are not covered by thin target data.

PPFX VALIDATION: PPFX before and After Modification

After Modification

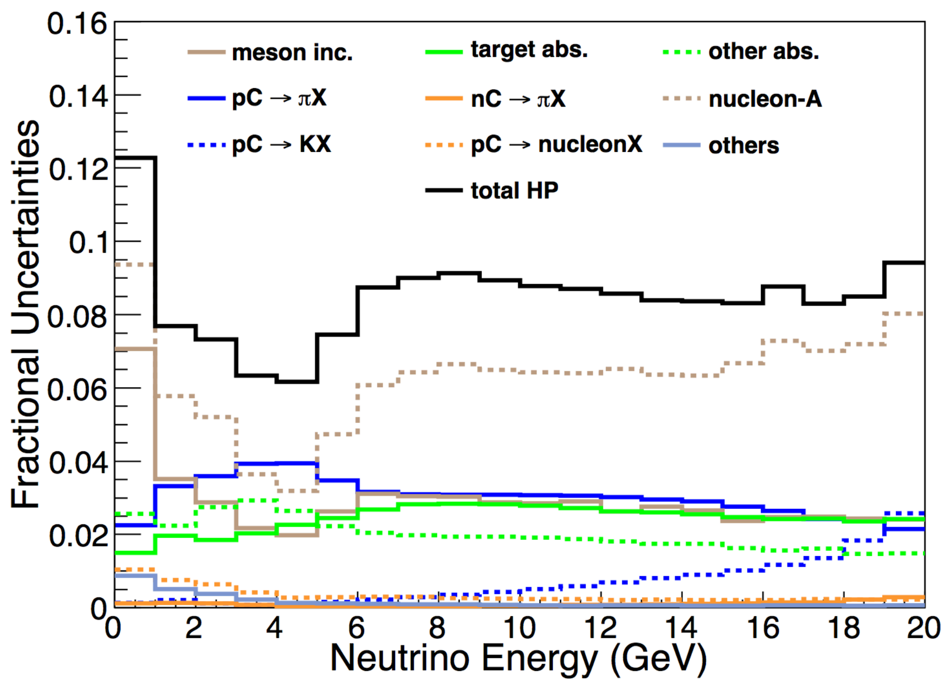


Before Modification

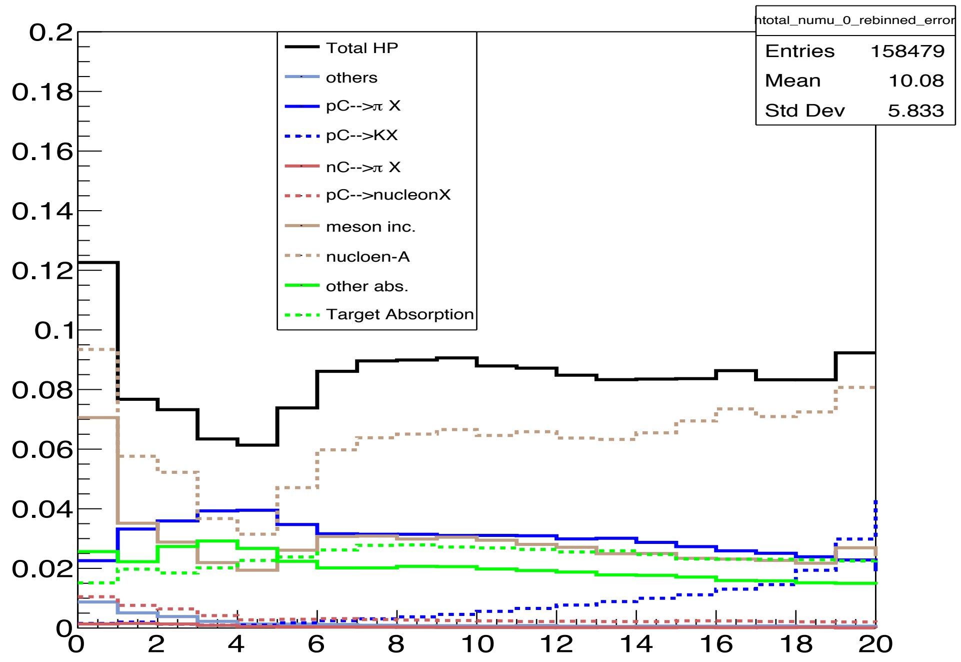


- Study done with 10 *100000 POTS.
- Using minerva ntuples.

PPFX Validation: PPFX before and After modification

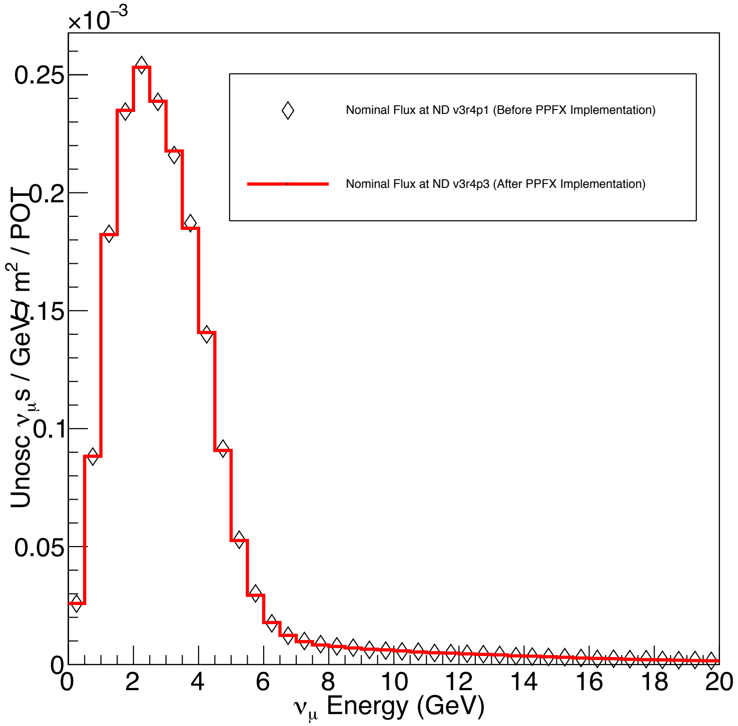


Fractional Uncertainty from Leo's Paper



Fractional Uncertainty from MINERvA ntuples by Amit after ppfx modification

PPFX Validation: G4LBNF Before and After PPFX Implementation



- Muon neutrino flux at the ND before and after the ppfx implementation with 120 GeV
- v3r4p1 flux used for flux before implementation(dotted)
- v3r4p3 flux used for flux after implementation (red line)
- Small disagreement might be due to statistics but in overall they are in good agreement.

PPFX VALIDATION

- Previous slides validate that the ppfx was implemented without affecting either g4lbnf or ppfx in its original form.

RESULTS

RESULTS

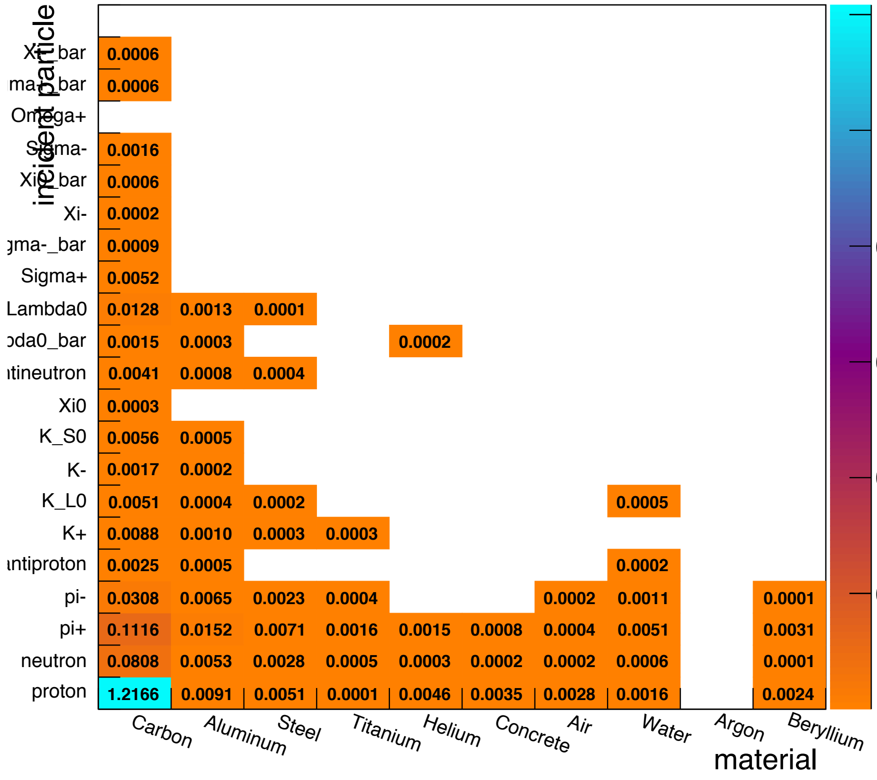
- Will look at Reference and Optimized (3 horn) design
  - Interactions per neutrino for different types of interactions
  - Interaction map
    - Interactions that are covered directly and with extensions
    - All Interactions
  - Fractional Uncertainty
  - Near Far Uncertainty

Interaction Map

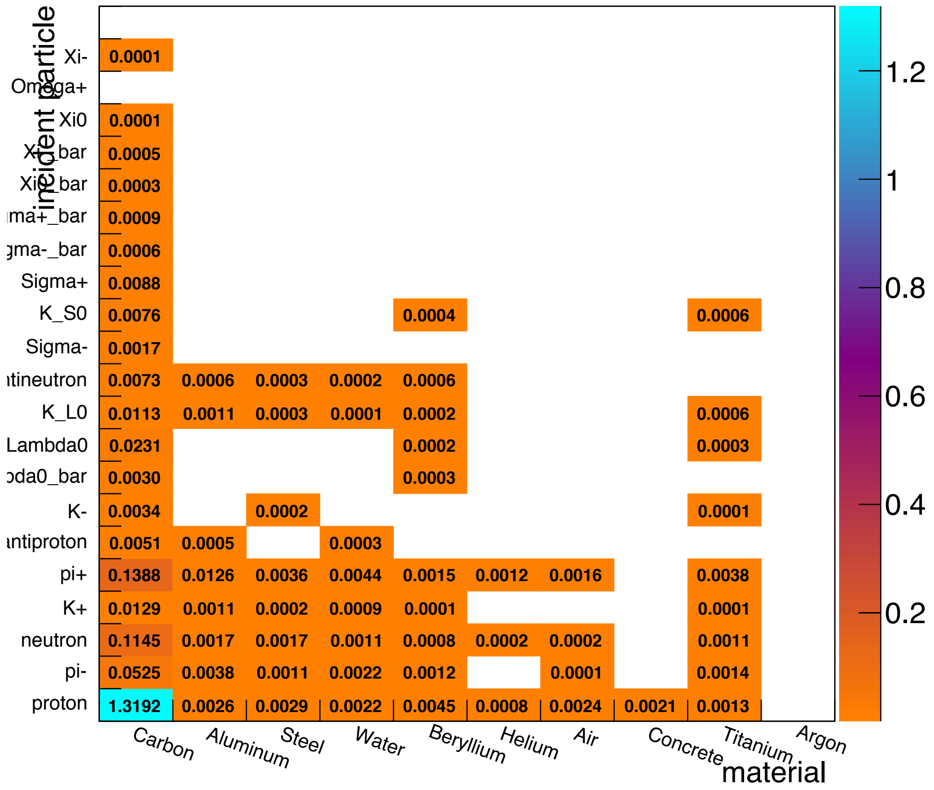
- Interactions per near detector neutrinos
- 120 GeV Protons
  - All Interactions
  - Interactions Covered by Thin Target Reweighters
    - Direct and Extended (see slides 37 to 41)

- Incident particles on various materials
- Pion Produced in various materials

All Interactions: Incident Particles

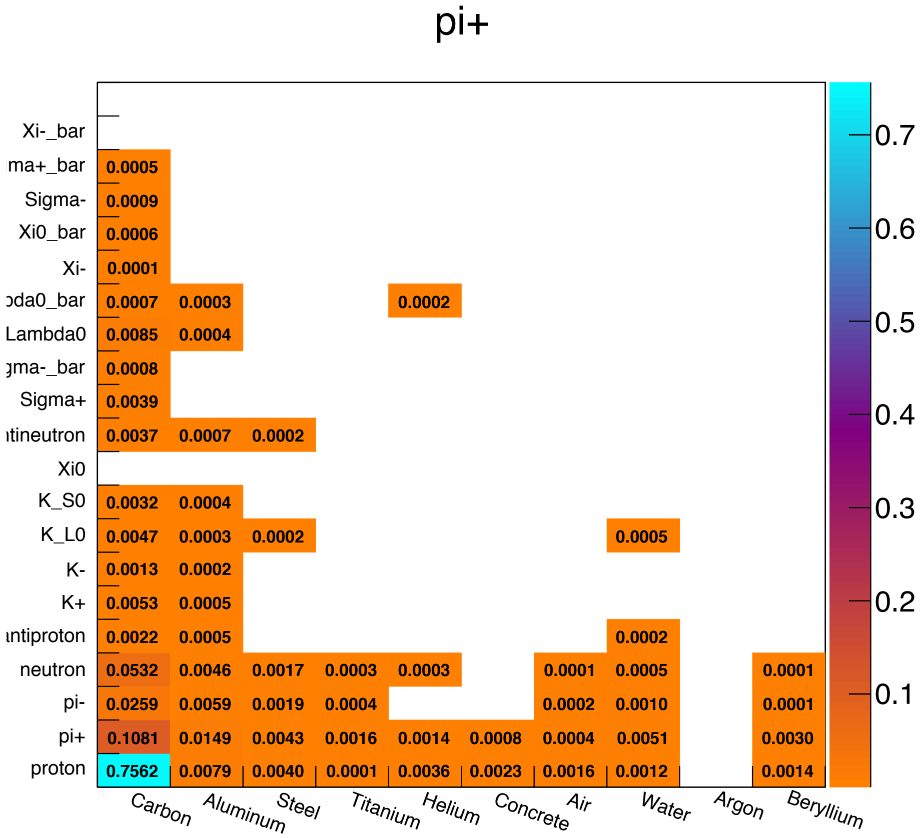


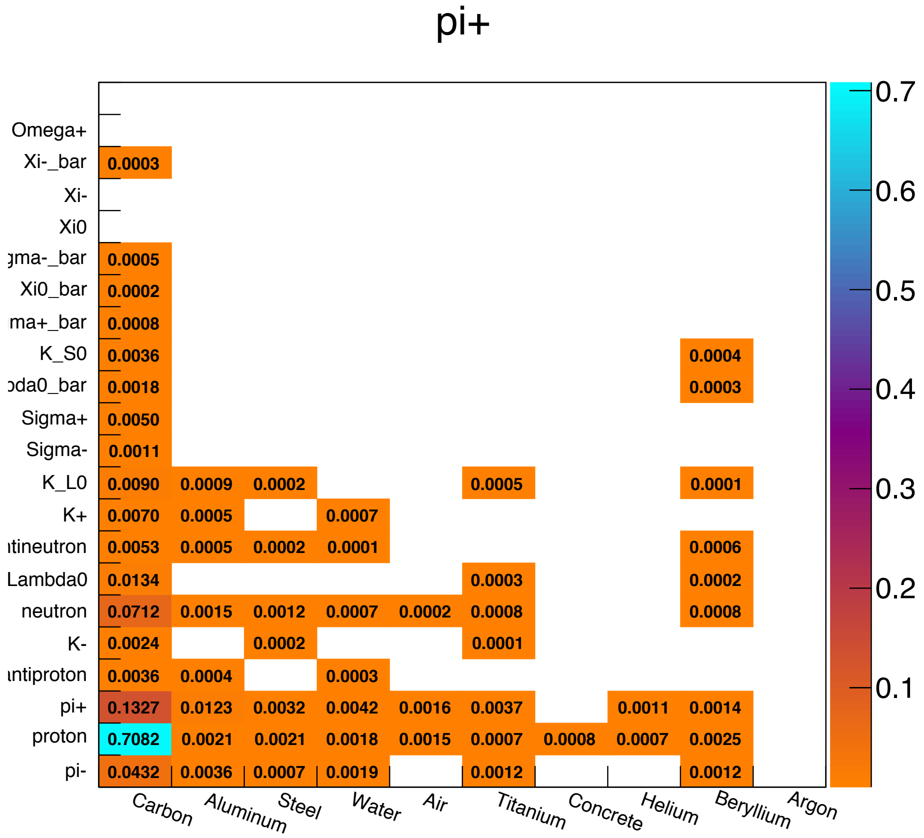
Reference 120 GeV



Optimized 120 GeV

All Interactions: Pion Production





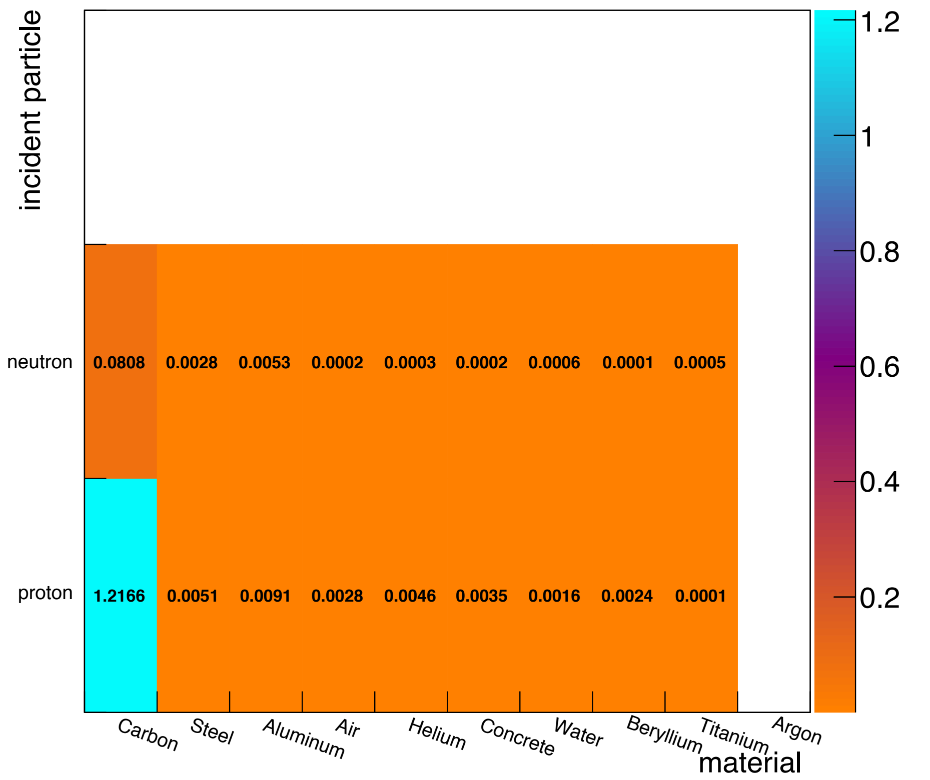
Reference 120 GeV

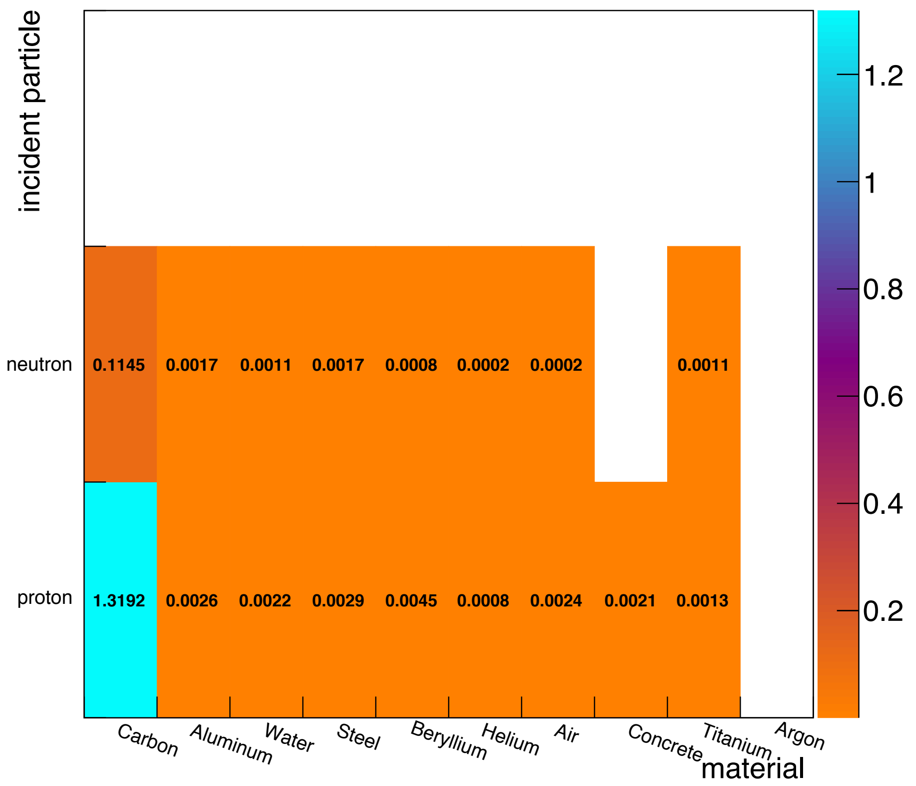
Optimized 120 GeV

Interaction Map

Interactions Covered by Thin Target Data (Direct and Extended)

Interactions: Incident Particles

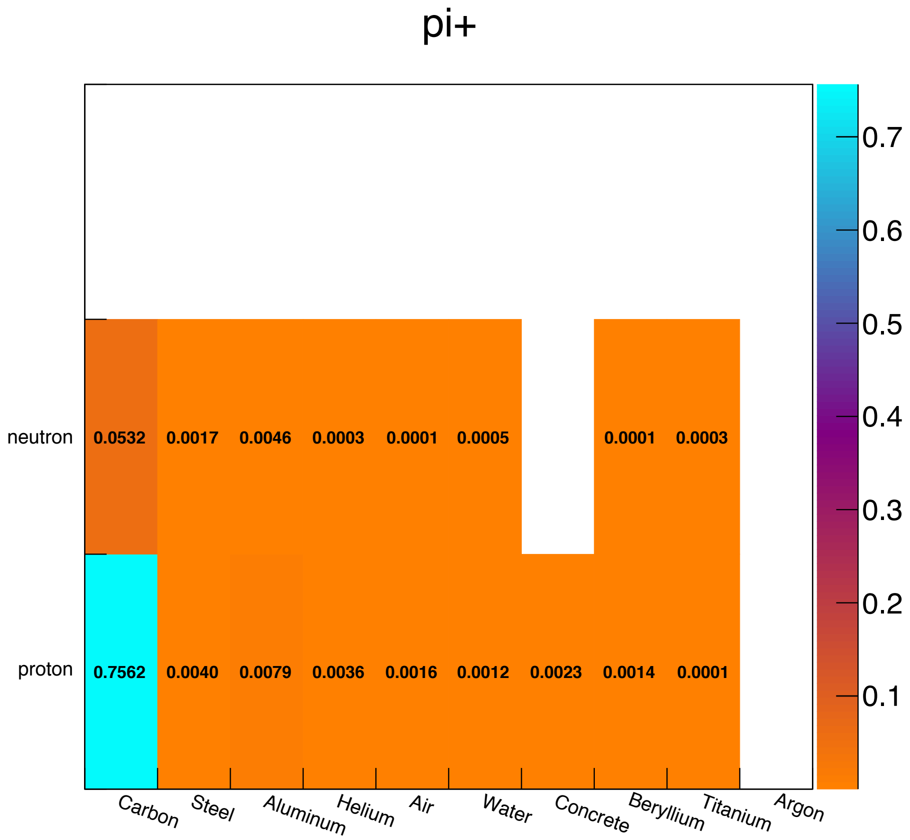




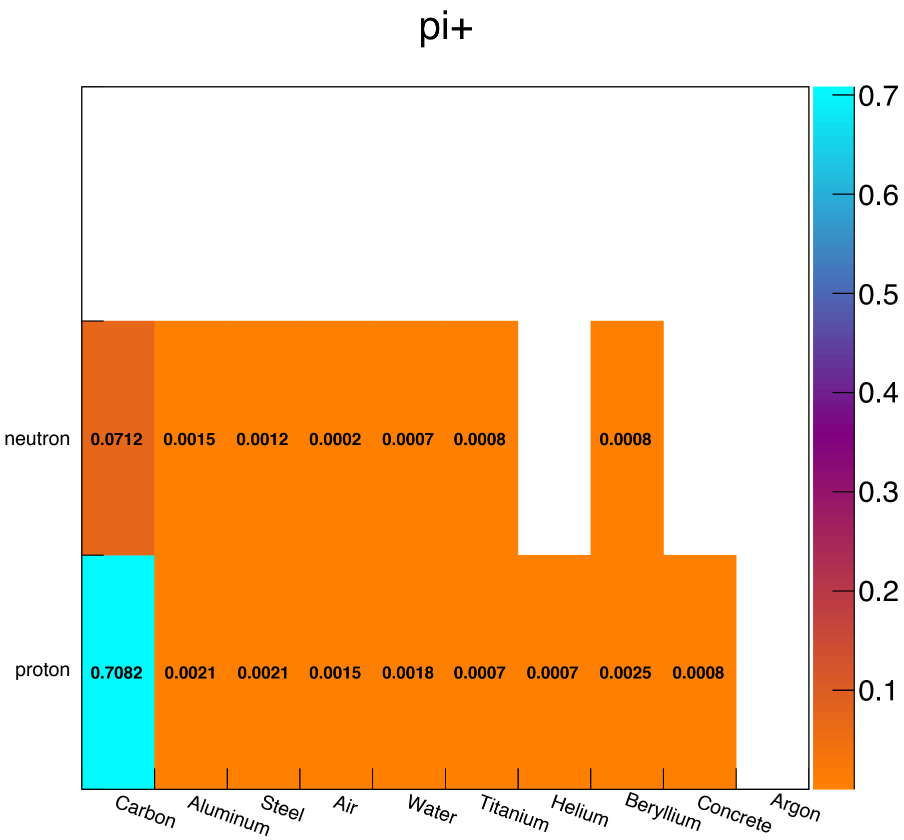
Reference 120 GeV

Optimized 120 GeV

Interactions: Pion Production

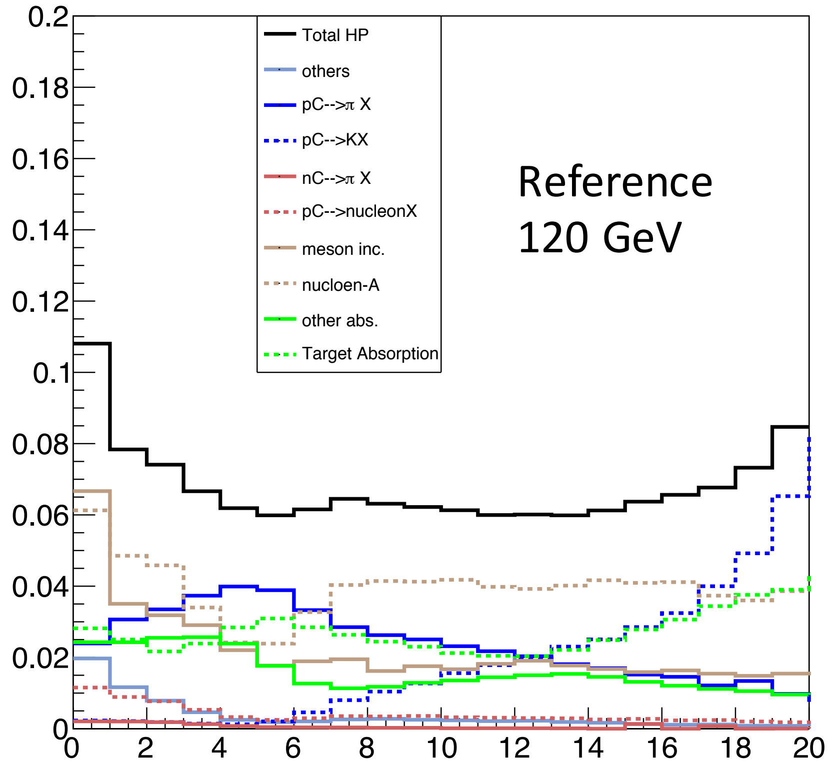


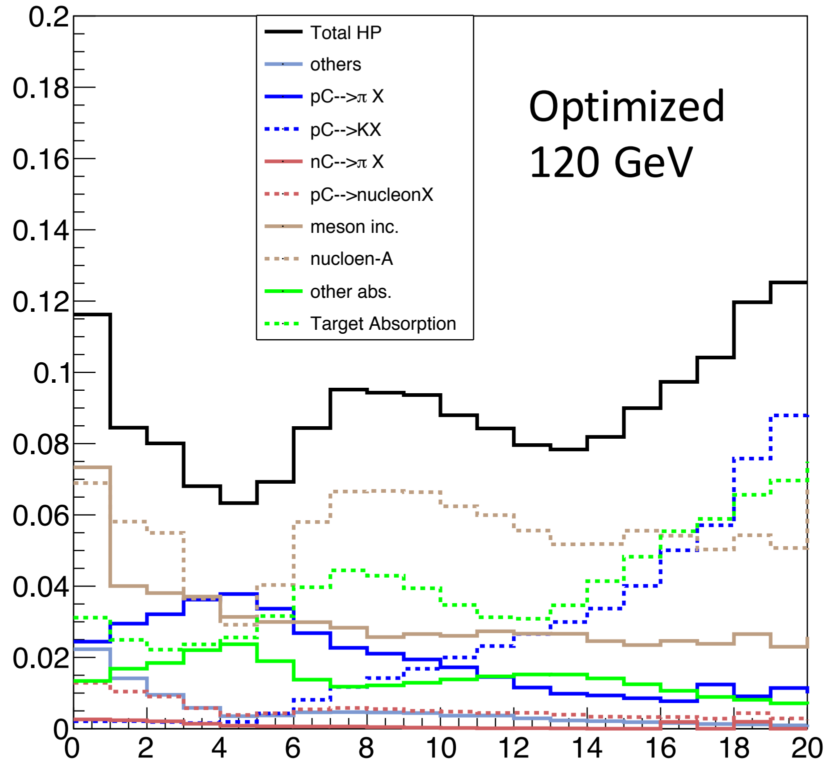
Reference 120 GeV



Optimized 120 GeV

Fractional Uncertainties : 120 GeV



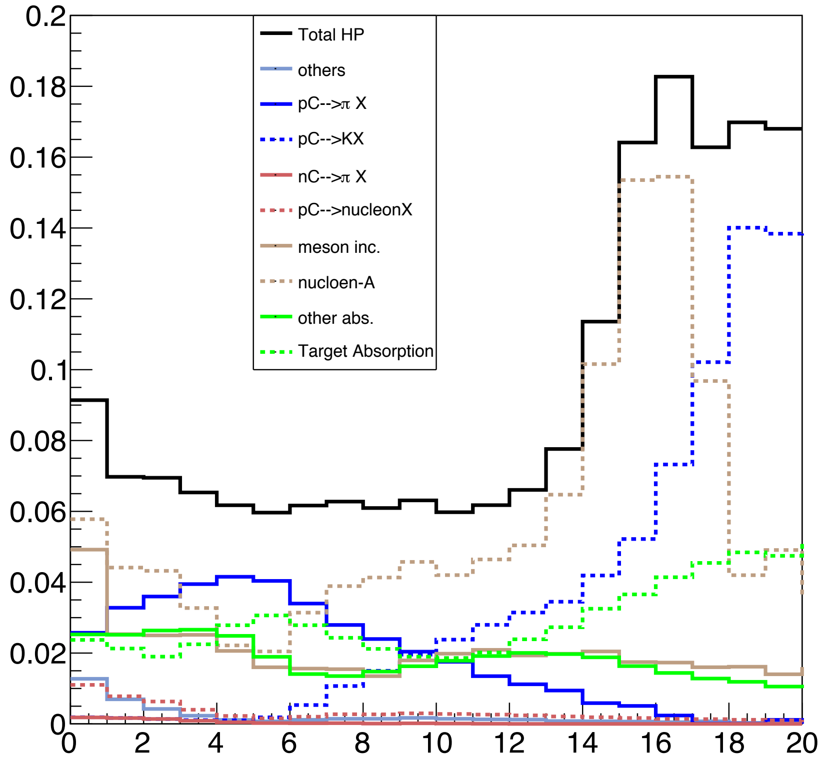


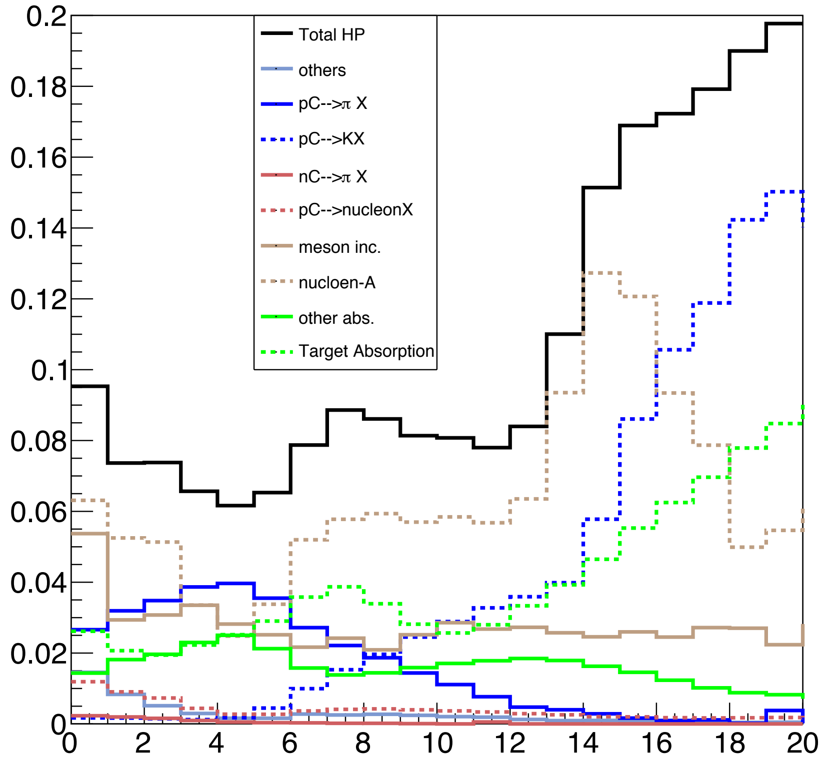
Dune Reference Design (Left)

DUNE Optimized 3 horn Design (Right)

120 GeV Proton Beam

Fractional Uncertainties: 80 GeV





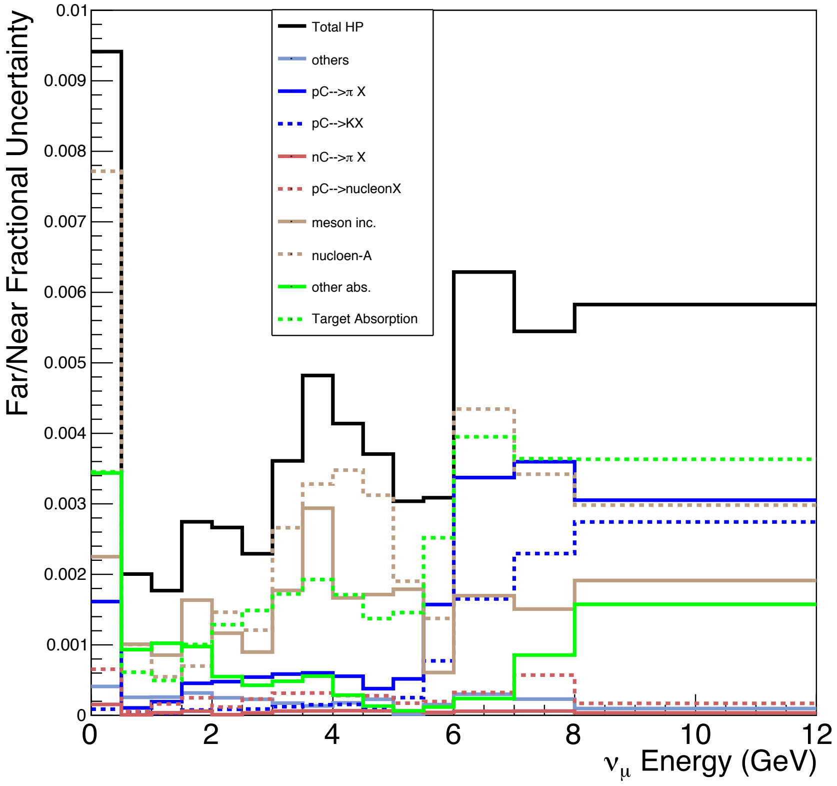
Reference: 80 GeV

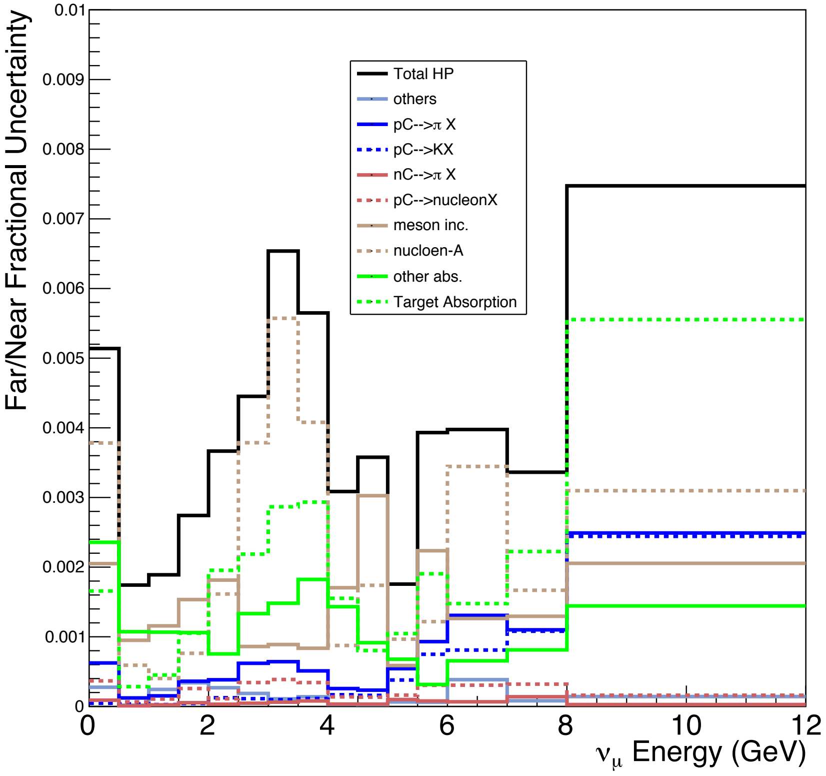
Optimized: 80 GeV

Near Far Fractional Uncertainties

- Near Far Fractional Uncertainties are the uncertainties from near far ratio
  - Doesn't include the detector effect
  - Flux projected at the center of the near and far detector

Near Far Fractional Uncertainties: 80 GeV





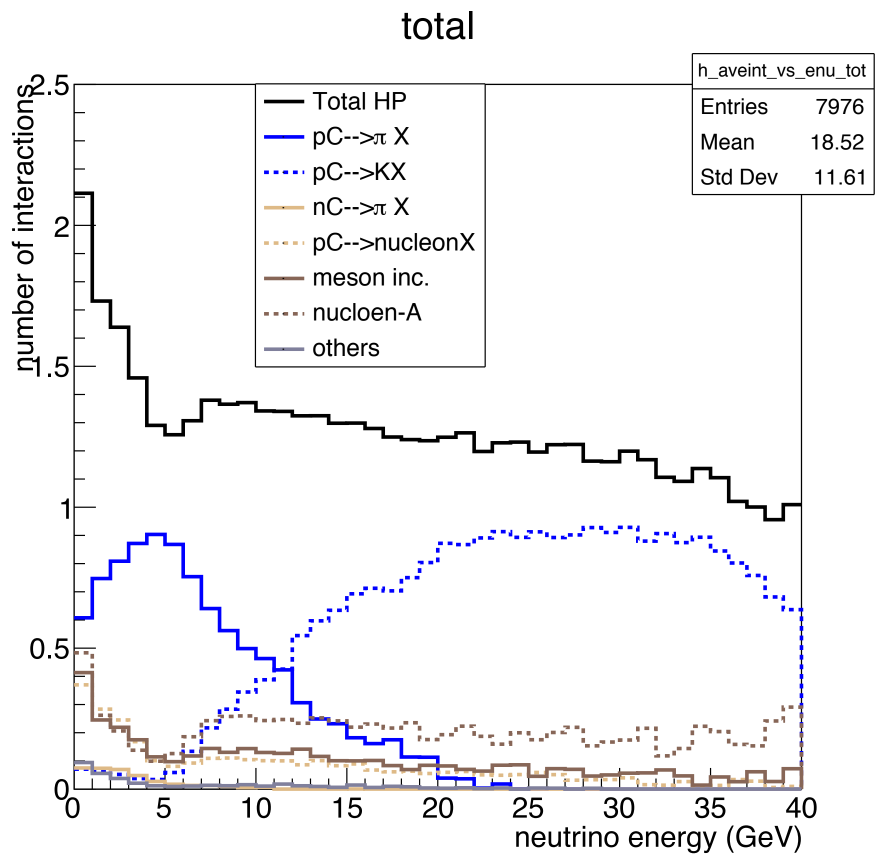
Reference 80 GeV

Optimized 80 GeV

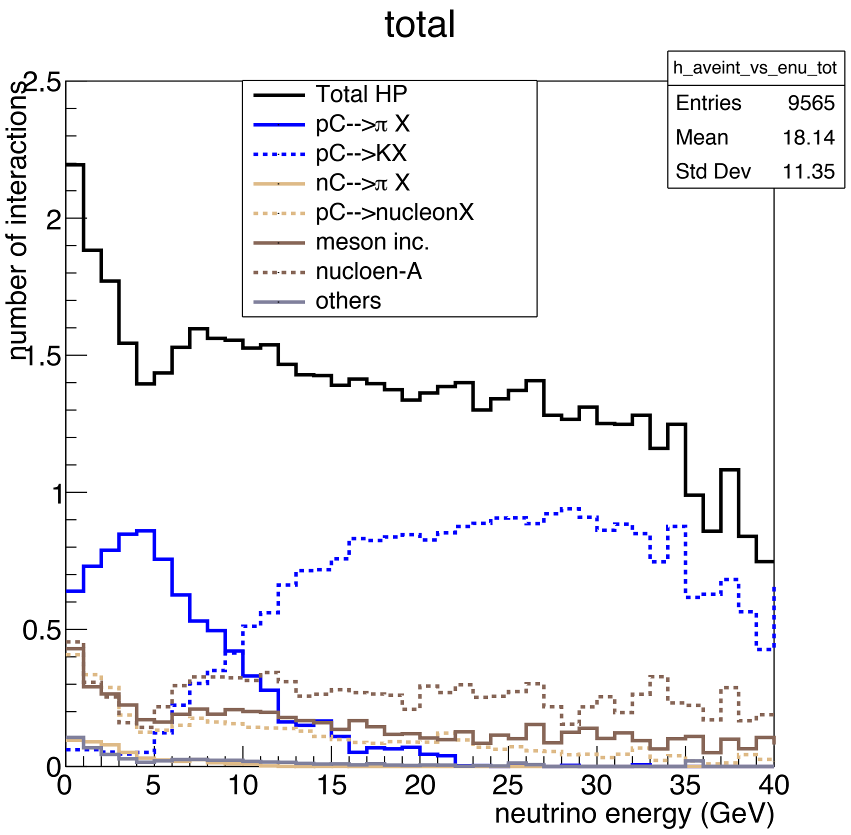
Interactions per Neutrino

- In this sections:
  - Interactions weighted neutrino flux at the near detector
  - Interactions are further categorized into interactions that are covered by various categories of thin target data
  - For example, in the next slide:
    - Solid blue line means interactions per near detector neutrino (flux projected at center of the detector) that are covered by proton on carbon giving pions thin target data.

Interactions per neutrino: 120 GeV

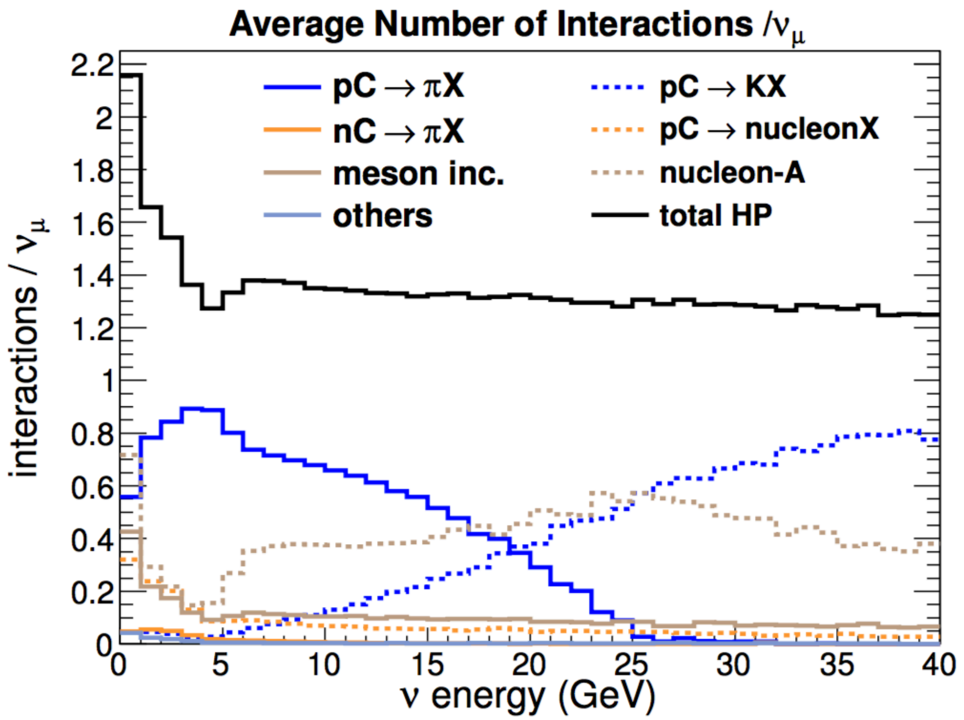


Reference: 120 GeV



Optimized: 120 GeV

Interaction Per Neutrino: NUMI



(a) ν_μ.

Interaction Per neutrino for NUMI.
(From Leo's Thesis)

Conclusions

- PPFX now compatible with dune and works properly.
- A technical note on the way. Explains:
  - How to use
  - Changes required in ppfx when working with new beamline designs
  - Changes required in g4lbnf when working with new beamline designs
  - Submitting jobs
  - Debugging small problems

Conclusions

- Right now:
  - PPFX compatible to dune not yet checked into ppfx repository
  - Wikipage: https://cdcvs.fnal.gov/redmine/projects/lbne-beamsim/wiki/PPFX_project
  - Contains path to ppfx that is compatible to g4lbnf.
  - Path to ppfx and g4lbnf modified to submit both ppfx and g4lbnf jobs parallely
  - Analysis tools in *g4lbne/BeamSimStudies/PPFX/*
  - README.txt files wherever needed.

TO BE DONE

- Upload the modified ppfx in CVS.
- Future improvements (most likely will be done by others)
  - Get MC Cross sections for geant4.10 QGSP_BERT for simulation
  - New Thin Target Data

BACK UP SLIDES

How is an interaction Handled by PPFX

I. Direct Data Coverage

UNDERSTANDING PPFX: *Covered by Data*

- When an interaction happens, a correction value is determined for each interaction:
- $c_i = \frac{N_i^{Data}}{N_i^{MC}}\ for\ any\ i^{th}\ interaction.$ [1]
- $c_i\ is\ the\ central\ value\ correction\ for\ the\ interaction\ that\ falls\ in\ the\ i^{th}$ *bin of the Hadron Production Data Set.*
- *Each bin has an associated uncertainty* σ_i and a covariance with other bins j, V_{ij}.

Covered By Data

- When a particle traverses through the volume, correction is:
  - $c(r) = e^{-\frac{N_A \rho(\sigma_{Data} - \sigma_{MC})}{A}}$ [1]

- When an interaction happens inside a volume:
  - $c(r) = \frac{\sigma_{Data}}{\sigma_{MC}} e^{-\frac{N_A \rho(\sigma_{Data} - \sigma_{MC})}{A}}$ [1]

  - Here:
  - C(r) is the central value correction
  - N_A is the number of atoms with atomic number A seen by the particle when it traverses the volume

When a Particle is Produced:

- When a particle is produced the correction is given by:
- $c(x_F, p_T, E) = \frac{f_{Data}(x_F, p_T, 158\ GeV)}{f_{MC}(x_F, p_T, E)} \times Scale(x_F, p_T, E)$ [1]
- Scaling done for 12,20,31,40,60,100,110,120 GeV [1]
- Linear interpolation for the intermediate energies
- $\Delta x_F = 0.005$ [1]
- $\Delta p_T = 0.025\ GeV/c$ [1]

Uncertainties for Each bin

- Since we use NA49 and Barton Data sets, the closest of the uncertainties from either data set is applied where the data sets overlap.
- Systematic uncertainties are 100% correlated between all bins
- Total systematic uncertainties are added by quadrature

How is an interaction Handled by PPFX

II. Extension of Data Coverage

Extension of Data Coverage

- Interaction outside the target in IC and Decay Pipe Wall
  - Parameterization of invariant cross section
  - $\frac{f(A_1, x_F, p_T)}{f(A_2, x_F, p_T)} = \frac{A_1^{\propto(x_F, p_T)}}{A_2}$ [1]
    - If A_1 is atomic number of Carbon and A_2 is the atomic number of other materials, $\propto$ is determined by independent fit of skubic data. [1,2]

Extension of Data Coverage

- Cross section of proton on carbon producing pions is extended to neutron on carbon producing pions using iso scalar symmetry

- Charged kaon production is extended to neutral kaon production by quark parton model.

How is an interaction Handled by PPFX

Covered by Data (Directly or by Extension)

Interactions not covered by Data

- Meson Incidents
- Particle produced in or out of target by re interacting proton

- Particle production in target by primary proton but outside the x_F range of Data (> .5 for pions and >.2 for kaons)
- For more info:
  - M. Jerkins, **MINERvA-docdb 7633-v1**, *Using Monte Carlo Models to Determine A Priori Flux Uncertainties*

Interaction Not Covered by Data: Uncertainties

- Uncertainty for these interactions is assigned 40% and they are un correlated.

Error Propagation by Multi Universe Method [1][3]

- When uncertainties are correlated:
  - N universes
  - Parameters and matrix of Parameters
  - Covariance matrix of parameters
  - Decomposition of Covariannce matrix by Chloskey method into upper and lower triangular matrix
  - Use lower triangular matrix to create the vector of deviates
  - Use the deviates to create N flux histograms for N universe
  - Use multi-variate Gaussian to get the final systematic uncertainty

REFERENCES AND FURTHER READING

- [1] **Neutrino Flux Prediction for the NuMI BeamLine**, Leonidas Aliaga Soplin, arXiv.org
- [2] T. Golan, **MINERvA –doc-11150-v1** (*For detailed skubic data fitting*)
- [3]. M. Kordosky, **MINERvA-doc-7433-v1** (*For detailed multi universe method for error propagation)*

IMPLEMENTATION OF PPFX IN DUNE

IMPLEMENTATION OF PPFX IN DUNE

- Before Proceeding to the implementation of the ppfx in DUNE:
  - Two bug fixes after the last presentation
  - Moving from "broken" two horn to "stable" three horn optimized design for the final design

Bug Fix 1: Particles exiting the target

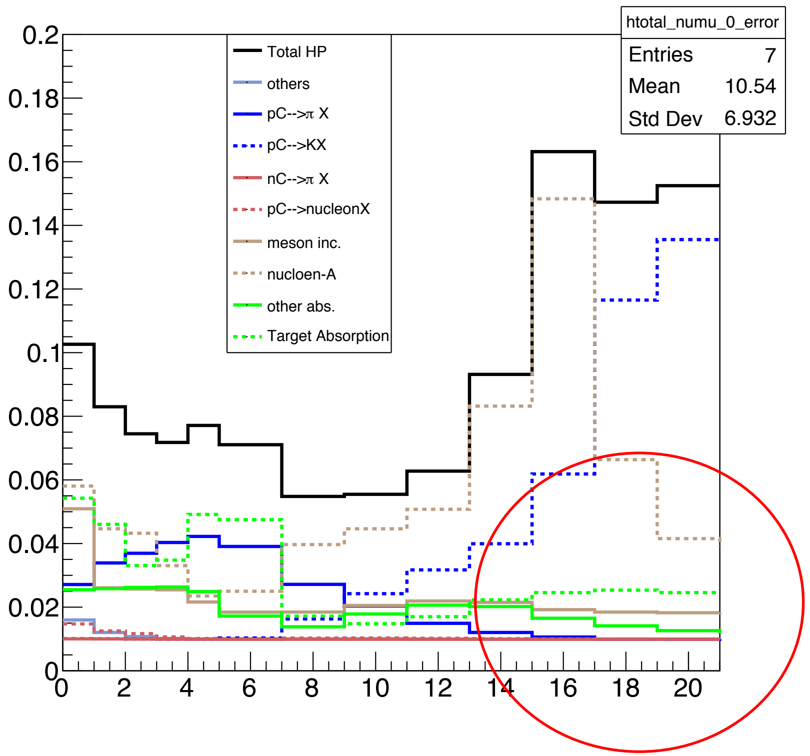
- Before, I had been recording the particles information that exited the target.
  - Before: Exit information recorded only for those neutrinos which parents exited the target (pC → X; X exits the target) and were produced from primary proton interaction only
  - i.e. particles that were produced by pC → X→Y….. (Y or any particle from ancestry longer than this exits the target) exit information was not recorded.
  - We fixed it.

Bug Fix 2: Fractional Uncertainties

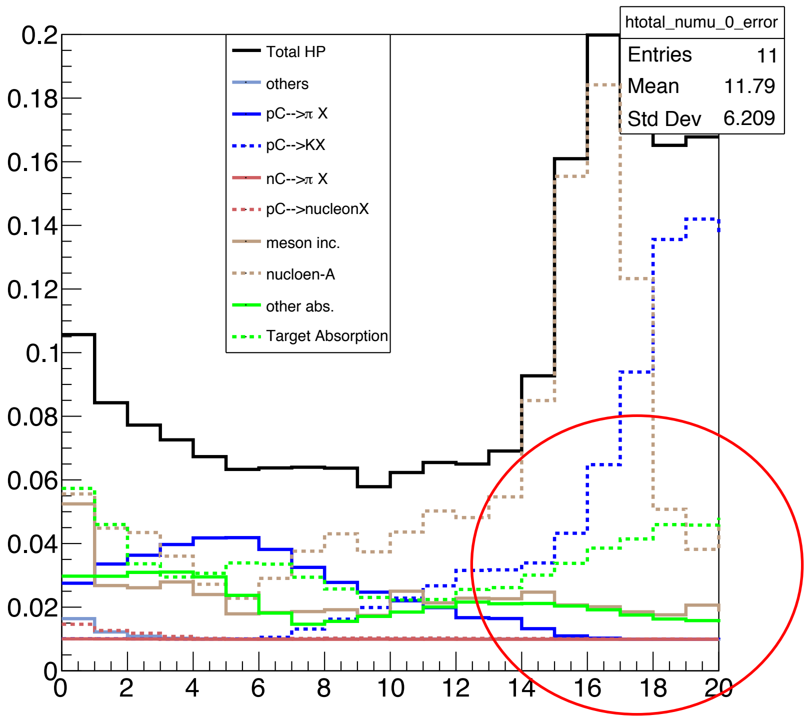
- While creating the fractional uncertainties, we were creating non empty histograms to fill in the uncertainties.
  - Gave slightly higher than actual uncertainties in each type of uncertainties
  - Effect more visible in the fractional uncertainties of the interaction type which should be close to 0.

  - The next 2 slides will show the effect of the bug. The binnings are different since I used old plots for comparison. Since the purpose of next two slides is just to show the effect of bug and not a qualitative assessment, I hope this will not matter.

Effect of Bug 1: Particles Exiting Target

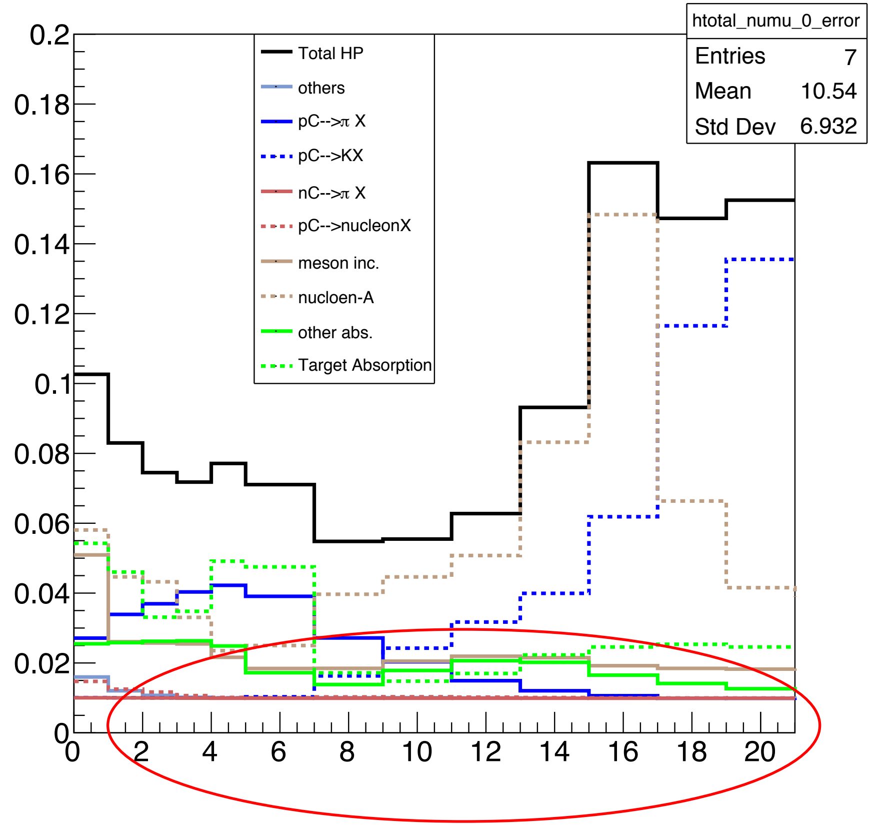


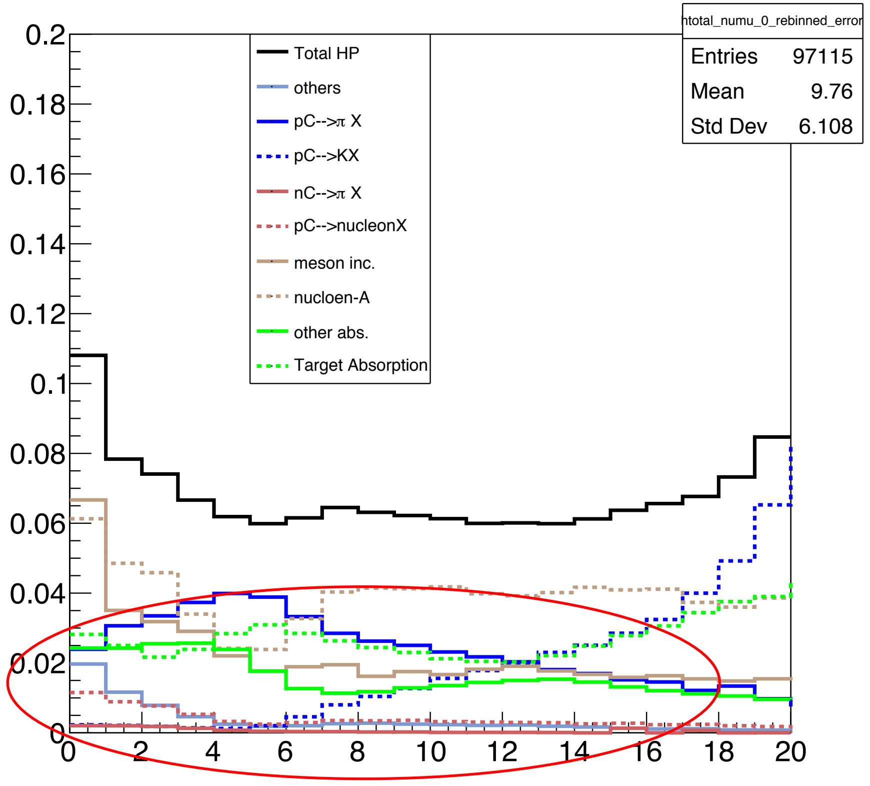
Reference before fix (80 GeV)



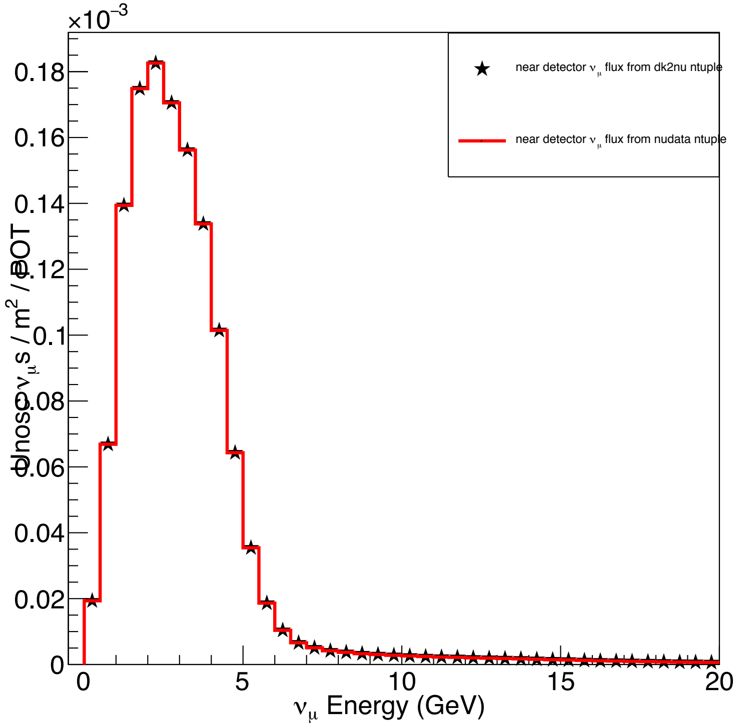
Reference after fix (80 GeV)

Effect of Bug 2: Fractional Uncertainty





PPFX VALIDATION: G4LBNF Before and After Modification



Muon neutrino flux at near detector (Reference Beam 80 GeV) using nudata and dk2nu ntuples after filling dk2nu information for ppfx.